DRAFT (REV D)
Hyperloop Design Specification
December 15, 2013

Forword *This is a draft version of the top level Hyperloop Design Specification. The objective of this document is to identify and gather together many of the design decisions and requirements for the specific Hyperloop design that will be used as the basis for feasibility validation, cost estimates and project planning.*

This draft specification is not intended to rigidly establish a specific, final design configuration. It is expected that through a process of review and analysis by the Hyperloop team, the configuration, design elements and requirements described in this document will be revised and the design more firmly defined over time.

While this draft specification is not intended to represent the final design configuration of Hyperloop, it none the less includes specific, detailed descriptions of configuration, interfaces, requirements, testing procedures and the like. The objective, indeed the necessity of this high degree of specificity is to surface and identify important detail considerations that must be addressed by the final design, and to establish a baseline for the interrelation of and interfaces between major elements of Hyperloop.

note: This Foreword is not intended to become a part of any final Hyperloop Design Specification. It is included in this draft to inform readers and reviewers of the author's intent.

1. **Scope** This document defines minimum requirements for a high speed transportation system comprised of transport capsules operated in a low pressure gaseous environment contained within tubes between connected points, hereinafter Hyperloop.

1.1 **Nomenclature**

1.2 **Classification** This specification applies to three distinct versions of Hyperloop suited to different functional applications.

1.2.1 **Hyperloop-F** is a configuration of Hyperloop intended for the transport of freight.

1.2.2 **Hyperloop-P** is a configuration of Hyperloop intended for the transport of passengers.

1.2.3 **Hyperloop-T** is the “test” configuration of Hyperloop intended for use in validating functional, performance, safety and other specific characteristics of Hyperloop. Parts of Hyperloop-T may at some point be incorporated into an instance of Hyperloop-F or Hyperloop-P

2. **Applicable Documents** The following documents shall form a part of this Specification to the extent specified herein.

2.1 **Government Documents**

2.2 **Commercial Documents**
Hyperloop Alpha Document
http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130812.pdf

Unit load device technical specification: IATA-354-27-ULD
Also see,
http://www.boeing.com/assets/pdf/commercial/startup/pdf/CargoPalletsContainers.pdf

3. Requirements

3.1 **Item Definition** Hyperloop consists of semi-evacuated tubes connecting Stations, through which travel Capsules carrying freight or passengers; together with supporting facilities and equipment, rights of way, contractual agreements, procedures, and documentation. The major components of Hyperloop covered by this Specification are limited to the Tubes, Capsules, Stations, and certain Supporting Facilities and Equipment.

3.1.1 **Item Diagrams** The following diagrams show the relationship and arrangement of major Hyperloop components and interfaces between Hyperloop and external systems.

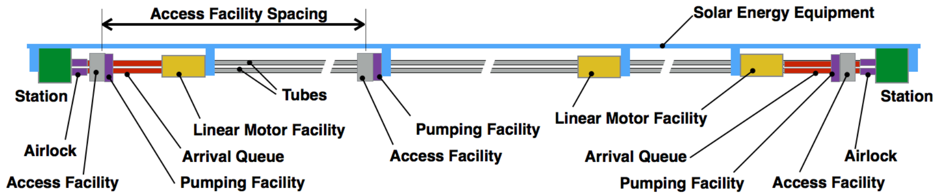
3.1.1.1 **Arrangement** Major components of Hyperloop are arranged as shown in Figure 3.1.1.1-1. Stations are located at each end of the Hyperloop route. Two capsule transport Tubes connect the stations in the Hyperloop-F and Hyperloop-P configurations. A single capsule Transport Tube connects Stations in the Hyperloop-T configuration.

Each Capsule transport Tube and associated equipment may be operated so as to convey Capsules in one direction or the other direction at different times. Tubes terminate with an Airlock at each Station. A section of Tube at each end, sufficiently long to “park” as many Capsules as may be in the Tube at any time is designated as the Arrival Queue Section. Linear Motor Facilities are placed along each Tube as necessary to achieve acceleration and deceleration of Capsules moving along the Hyperloop route. The spacing of Linear Motor Facilities varies with the grade and design Capsule speed along the route.

At the end of each Arrival Queue Section closest to the respective terminating Airlock, and at regular intervals along the Tube, Access Facilities and Pumping Facilities are located. An access Facility or a Pumping Facility serves both Tubes at their location for Hyperloop configurations wherein there exist two Tubes and said Tubes are adjacently disposed at the Access Facility / Pumping Facility.

Solar panels are disposed along the Tubes and at Hyperloop Facilities. Balance of System (BoS) components supporting these solar panels consist of line-connected power inverters and may also include storage batteries. BoS components located at a given Hyperloop Facility support only Solar Panels near to said Facility. All Facilities are connected to the commercial power grid and Facilities with BoS components are able to exchange energy with the grid as needed. If power generated or energy stored at one Facility is to be supplied to another Facility that power will be transferred via the commercial grid.

*There is **no provision** within Hyperloop for transferring power between facilities independent of the commercial power grid.*



Arrangement of Hyperloop Components

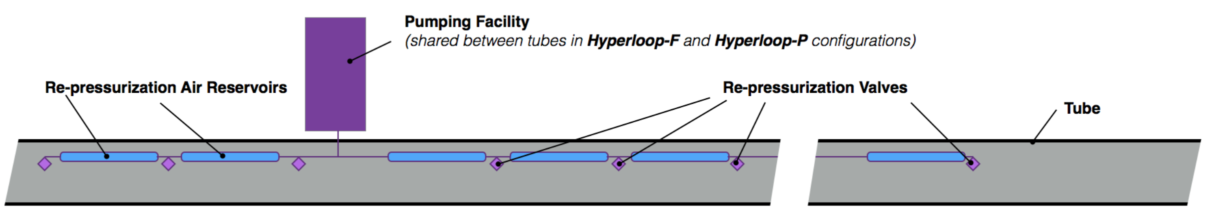
*(**Hyperloop-F** and **Hyperloop-P** have two (2) tubes as shown, **Hyperloop-T** has one (1) tube only.)*

*Note: Each Hyperloop **Tube** can support **Capsule** travel in either the right-to-left direction, or the left-to-right direction, but not in both directions at the same time. In normal operation of **Hyperloop-F** or **Hyperloop-P**, one **Tube** conveys **Capsules** in the left-to-right direction and the other **Tube** carries Capsules in the right-to-left direction such that a continuous flow of capsules between **Stations** may be maintained.*

FIGURE 3.1.1.1-1

3.1.1.2 **Re-pressurization Components** Hyperloop includes provision for rapid re-pressurization of a Tube. The Re-pressurization System is comprised of high pressure Re-pressurization Air Reservoirs disposed along the interior of each Tube and similarly disposed Re-pressurization Valves that admit compressed air from the Reservoirs into the Tube rapidly and uniformly along the length of the Tube. This arrangement is illustrated in Figure 3.1.1.2-1. The volume of the Reservoirs and the level of pressurization are controlled such that when the Reservoirs are emptied fully into a tube at normal operating (evacuated) pressure, the pressure within the Tube and the Reservoirs equalizes at 1 Atmosphere.

Re-pressurization Reservoir “strings” are connected with tubes sized to limit the air discharge rate in the event of a tube rupture or fitting failure. Reservoir strings are charged with dried, cooled compressed air supplied from a pumping facility. Reservoirs comprising a string connected to a given pumping facility are not connected to adjacent Reservoir strings fed from adjacent Pumping Facilities



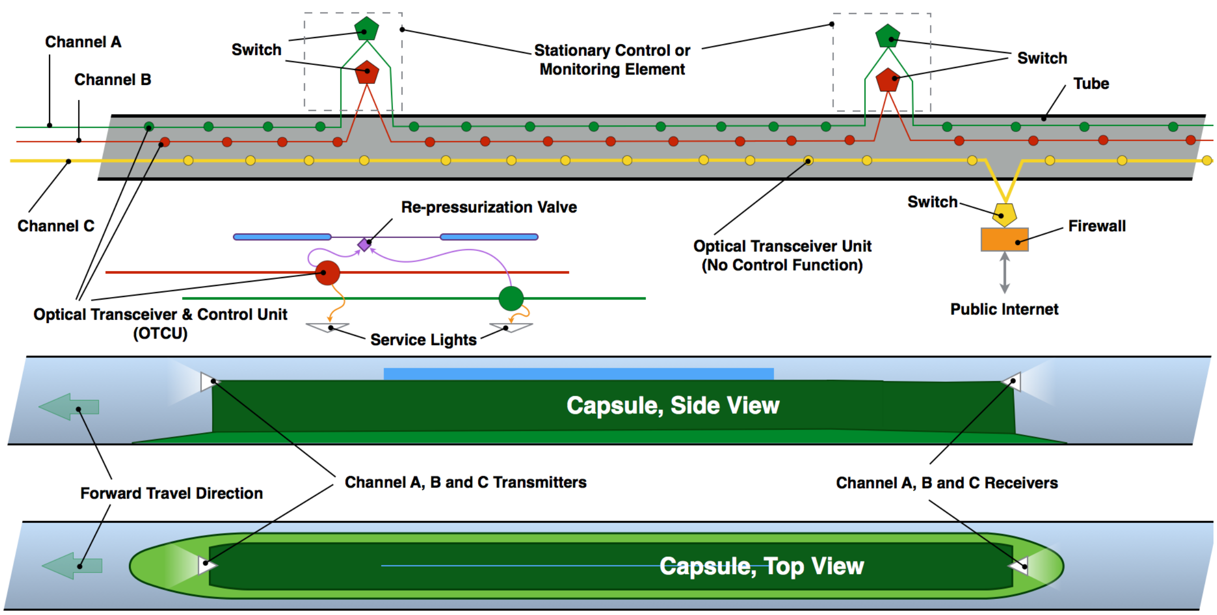
Re-Pressurization System

Each Hyperloop Tube is equipped with a Re-pressurization System that allows prompt re-pressurization of the tube to ambient (≈1 Atm.) pressure while limiting temperatures within the tube, i.e. without inducing excessive adiabatic heating.

FIGURE 3.1.1.2-1

3.1.1.3 **Communication System** Digital information is transferred to and from Capsules in Hyperloop by short range, full duplex optical links. Optical Transceiver Units (OTU) are located at regular intervals along the inside of Tubes and elsewhere such that every Capsule can maintain constant communication. Three communication channels are designated Channel A, Channel B and Channel C and for each Channel an independent set of OTUs is connected via a redundant, counter-rotating ring topology data transport system using copper interconnect (due to the relatively close spacing of OTUs). Arrangement of communication system elements is shown in Figure 3.1.1.3-1. Individual OTUs function as Add Drop Multiplexors (ADMs) on their respective channel.

Communications are packet based, Internet Protocol on all channels. Each OTU maintains an “ephemeris” for each Capsule based on Capsule location, speed and direction information “published” on each Channel at regular intervals by the Hyperloop Control System. Based on the “ephemeris”, exactly one OTU will handle each data packet sent to or from a Capsule.



Communication System

Two independently powered, physically isolated data networks, logically isolated from the Internet are used for control and monitoring of ***Hyperloop****.*
The ***Hyperloop-P*** *configuration only includes an additional, independent network that provides Internet access through a dedicated Router and Data Security Facility.*

FIGURE 3.1.1.3-1

3.1.1.3.1 **Channel Separation** Separate A, B and C Channels are implemented for each Hyperloop Tube. Channels A, B, C use separate wavelength pairs for communication with Capsules. These wavelengths are listed in Table 3.1.1.3-2. Channels A and B are dedicated to Hyperloop control and monitoring functions, are connected to various Hyperloop

control elements, and these Channels and all equipment connected to these Channels is strictly isolated from the public Internet.

Channel C functions to distribute Public Internet service to passengers traveling in the Capsules and is present only in the Hyperloop-P configuration.

Channel	Transmission to Capsule	Transmission from Capsule
A	780 nm	904 nm
B	808 nm	980 nm
C	840 nm	1310 nm

TABLE 3.1.1.3-2

3.1.1.3.2 **Channel Bandwidth** TBD

3.1.1.3.3 **Auxiliary OTU Functions** Channel A and B OTUs, in addition to functioning as part of the respective optical communication channel, perform the following auxiliary functions.

3.1.1.3.3.1 **Service Lighting** OTUs on Channels A and B, and located within the Tube function to power co-located service lighting fixtures.

3.1.1.3.3.2 **Re-pressurization Functions** OTUs on Channels A and B, and located within the Tube function to control and monitor elements of the Re-pressurization System described in Section 3.1.1.2.

3.1.1.3.3.3 **Other Auxiliary Functions** TBD (Surveillance Cameras, Speaker-Phone, Thermal/Acoustic/Electromagnetic monitoring of passing Capsule signatures - for maintenance…??)

3.1.1.4 **Access Facility** Access Facilities provide access to the interior of the Tube(s) for the purpose of inspection, maintenance, insertion / extraction of capsules and maintenance vehicles, and for recovery / removal of disabled / stranded vehicles , passengers or personnel. Access Facilities provide access to Tubes ONLY when Tubes are at normal atmospheric pressure. When a Tube is evacuated to operating pressure there is no access to the Tube interior via Access Facilities. The general configuration and key features of an Access Facility are illustrated in Figure 3.1.1.4-1.

Each Access Facility includes an overhead Crane with the ability to lift, lower, translate, rotate, insert and remove, Capsules and Support Vehicles.

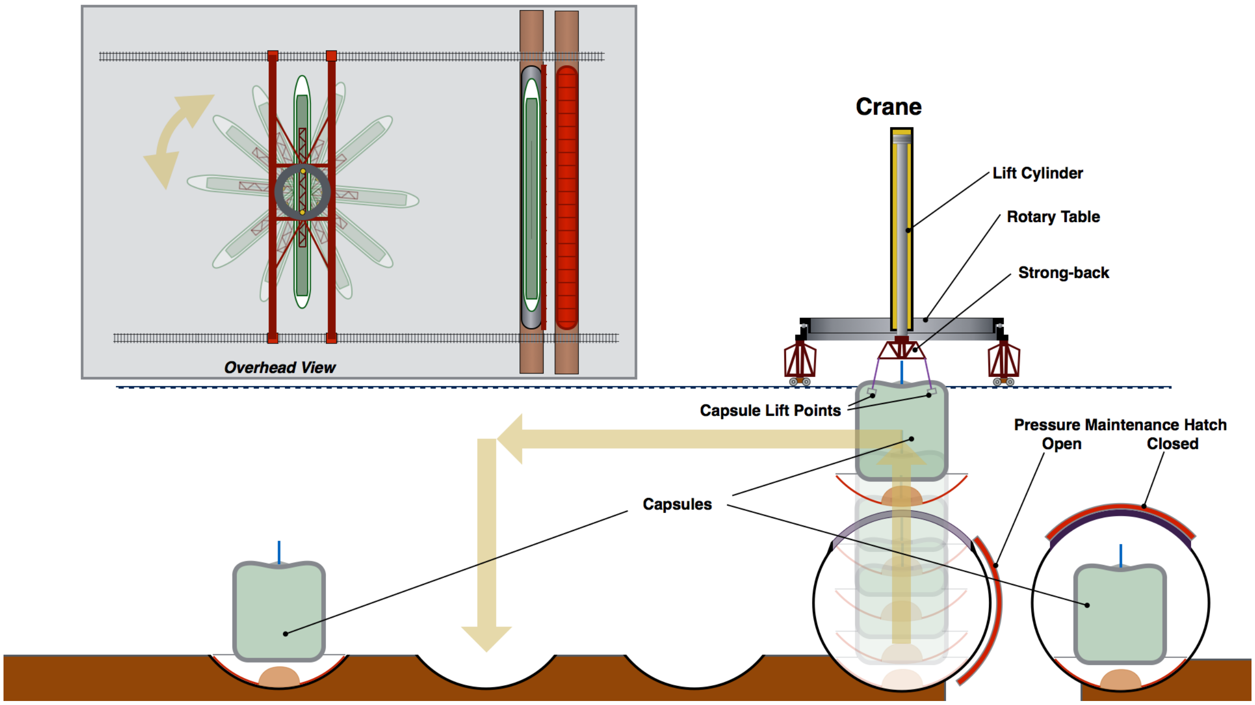


FIGURE 3.1.1.4-1

3.1.1.5 **Pumping Facility** Each Pumping Facility supplies dry, cooled, compressed air to charge adjacent sections of the Re-pressurization System (Section 3.1.1.2); supplies vacuum for evacuating the Tube(s); and low pressure, filtered air for ventilating the Tube(s) when open to atmosphere. In Hyperloop-F and Hyperloop-P configurations, the equipment of a Pumping Facility may be used to service either Tube.

3.1.1.6 **Linear Motor Facility** TBD

3.1.1.7 **Solar Power System** TBD

3.1.1.8 **Stations** Features supporting the following capabilities shall be included in Hyperloop Stations as appropriate for specific Station locations.

a) Station design shall support operation of each terminating Hyperloop Tube in either direction, that is for either departures or arrivals. *(This functionality is necessary to support alternating direction operation of one of two Tubes of Hyperloop-F or Hyperloop-P during times that the other Tube is shut down for maintenance, and also to support alternating, bi-directional traffic in the Hyperloop-T configuration.)*

b) Station design in the general case, shall support termination of multiple Hyperloop routes, the interchange of Capsules between

routes, and the transfer of passengers arriving on one route to Capsules departing on another route (i.e. Like a 'hub' airport operating in a hub-and- spoke route system.)

c) Station design shall provide for Capsule recharging between trips, transfer of capsules between “service” and “maintenance”, transfer of Capsules between the Access Facility adjacent to the Station (Sections 3.1.1.1 & 3.1.1.4) and Arrival and Departure ports of the terminated Hyperloop(s).

d) Stations shall have sufficient Capsule storage space, terminal facilities, charging facilities and maneuvering capacity such that all Capsules that may at one time be inbound can be received, processed through terminal facilities, sequenced through charging facilities, stored and eventually dispatched in the event that all departure facilities of the station become and remain inoperable.

The following Station features shall be implemented to the extent necessary to achieve capabilities a - d, above.

3.1.1.8.1 Tube Termination

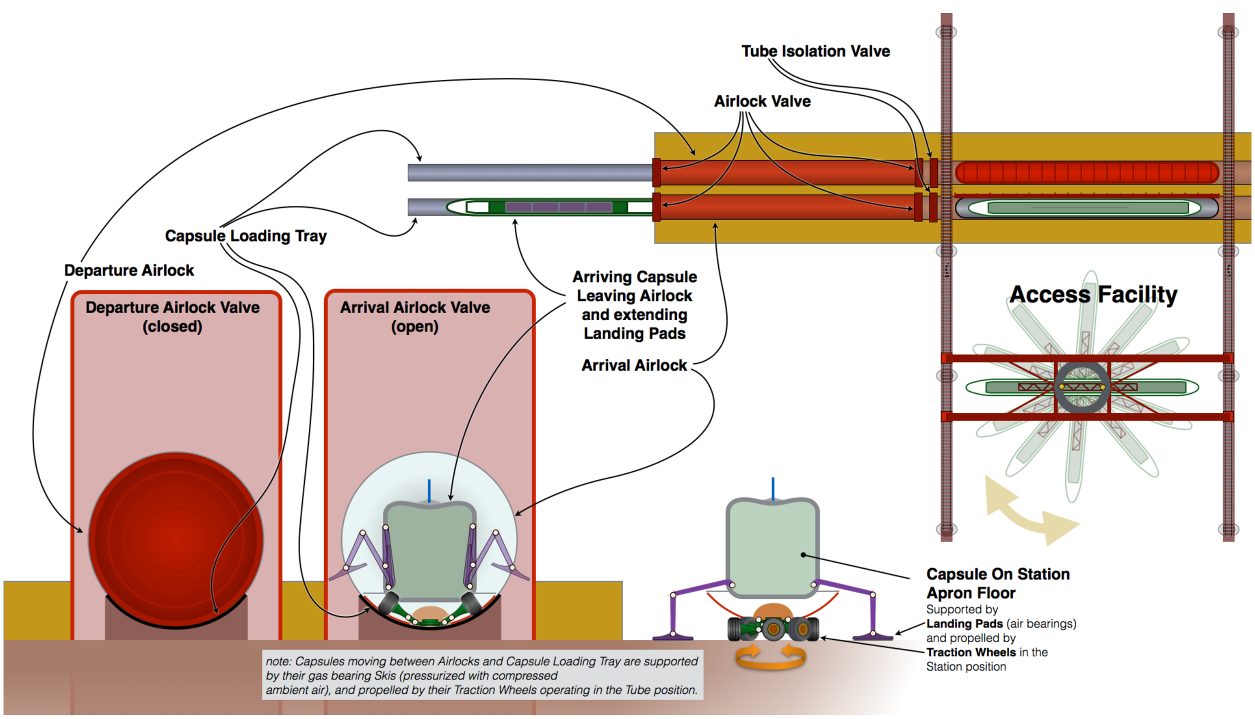


FIGURE 3.1.1.8.1-1

3.1.1.8.1.1 Capsule Loading Tray

3.1.1.8.1.2 Airlock

3.1.1.8.1.2.1 Departure Cycle

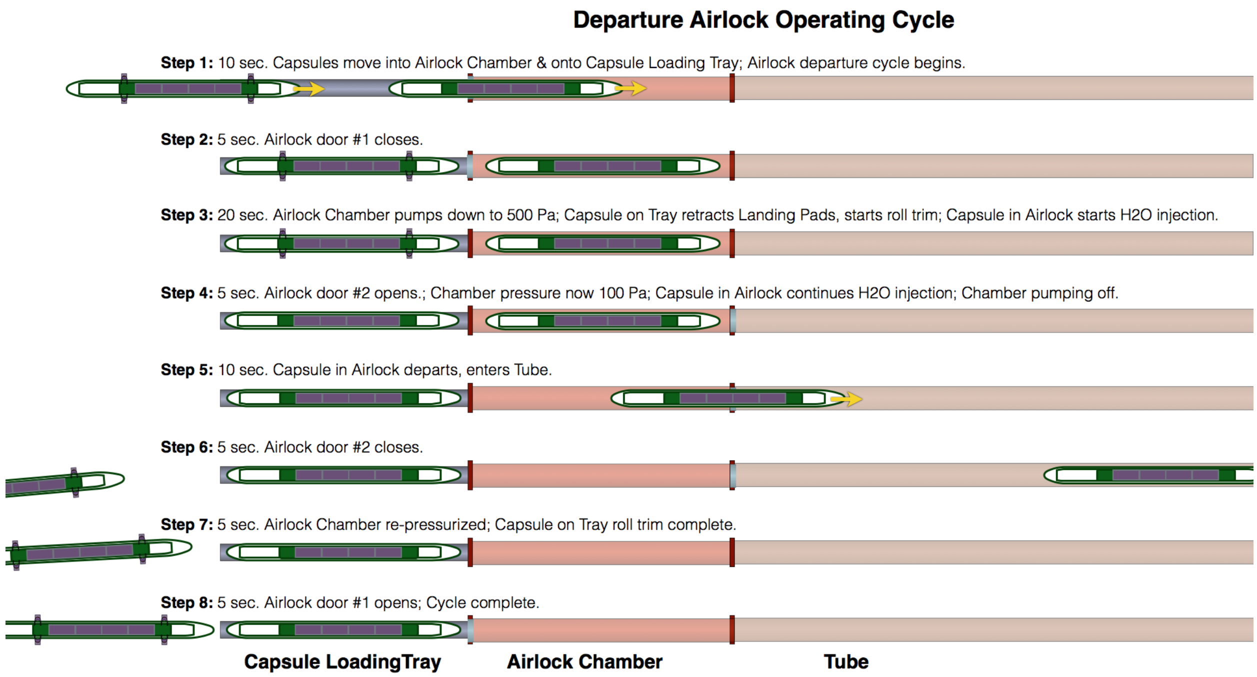


FIGURE 3.1.1.8.1.2.1-1

3.1.1.8.1.2.2 Arrival Cycle

Arrival Airlock Operating Cycle

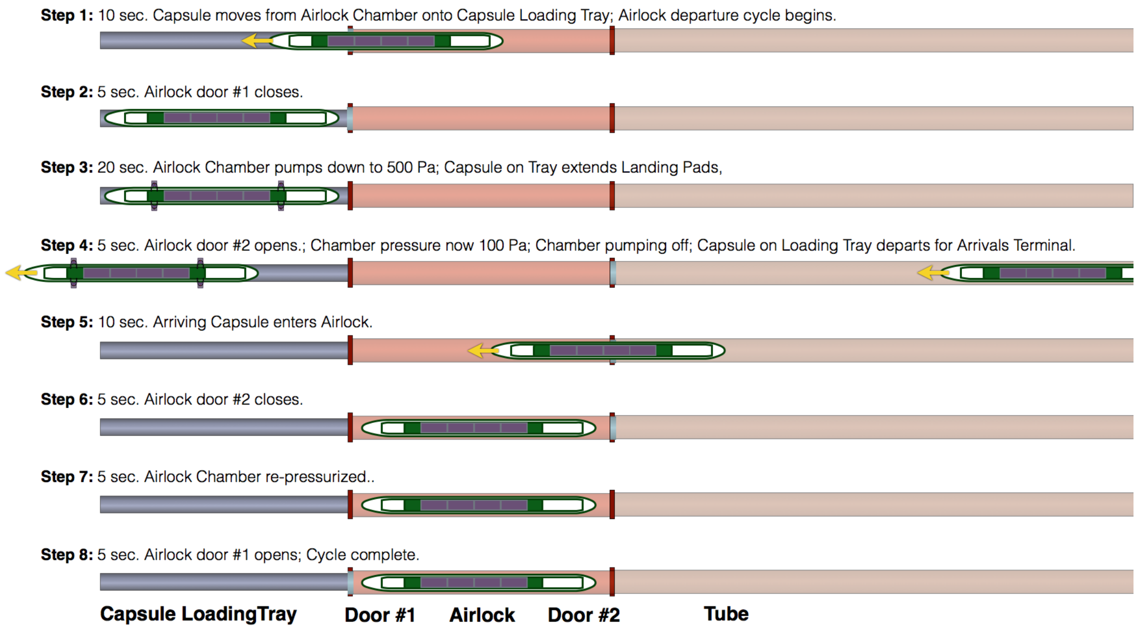
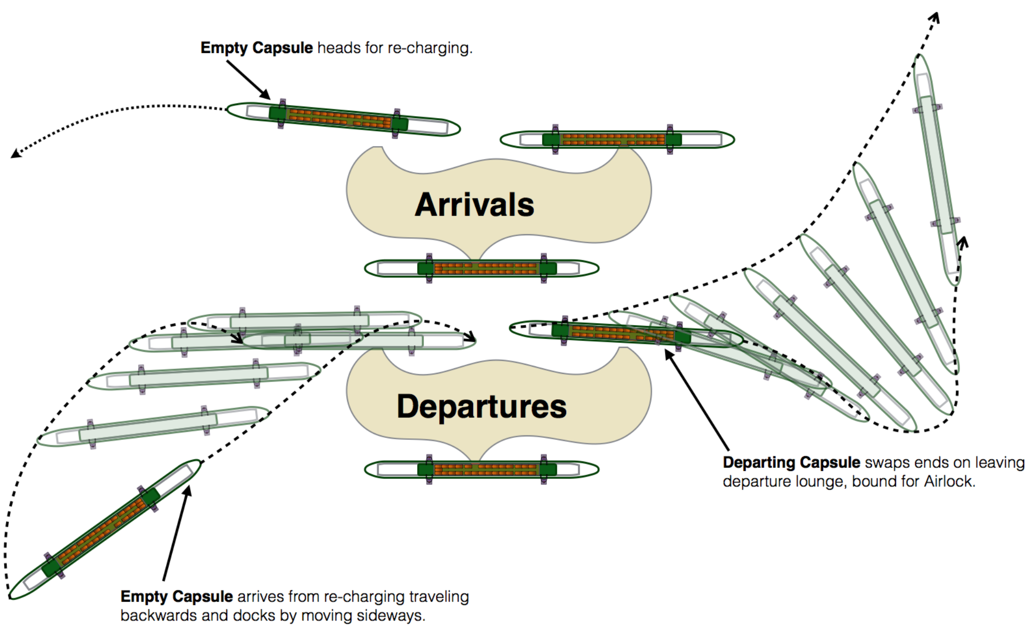


FIGURE 3.1.1.8.1.2.2-1

3.1.1.8.2 Apron



Capsules Maneuvering on Station Apron Floor

FIGURE 3.1.1.5.2-1

3.1.1.8.3 **Terminal Facilities**
3.1.1.8.4 **Recharging Facilities**
3.1.1.8.5 **Maintenance Facilities**
3.1.1.8.6 **Administrative and Security Facilities**

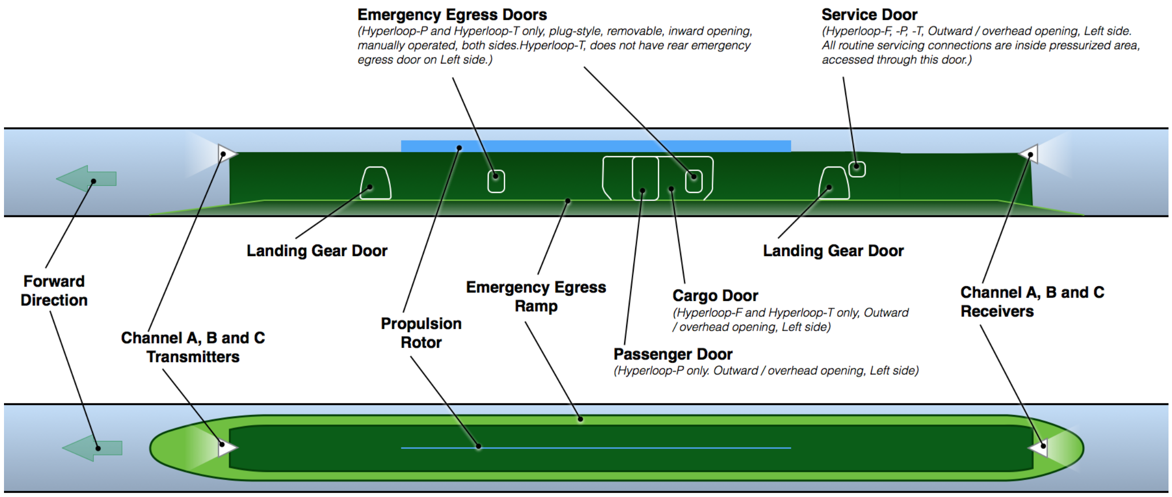
3.1.1.9 **Supporting Equipment** TBD

3.1.1.10 **Capsules** External Capsule configuration is illustrated in Figure 3.1.1.10-1. Hyperloop-F and Hyperloop-T are equipped with a cargo door suitable for LD-6 Unit Load Devices (ULD). Hyperloop-P is equipped with a passenger door. The passenger and cargo doors are sealed and cannot be opened - even in an emergency - while a Capsule in inside the Airlock or Tube.

3.1.1.10.1 **Emergency Egress** Emergency egress from a Capsule that is in an Airlock or Tube is ONLY possible through the Emergency Egress Doors, which are of the removable 'plug' type. The Emergency Egress Doors are held closed by Capsule internal pressure and are inoperable while in an evacuated Airlock or Tube.

3.1.1.10.2 **Emergency Egress Ramps** Capsules are equipped with external walkways consisting of a "running board like" walkway on either side that covers Capsule mechanisms, and sloped platforms at the front and back that align with the Tube interior form. The function of the Capsule Emergency Ramp is to facilitate passenger egress from a stopped Capsule while inside an Airlock or Tube, and to facilitate the

passage of passengers or other personnel around a Capsule stopped in a Tube or Airlock



Capsule External Configurations

FIGURE 3.1.1.10-1

3.1.1.10.3 **Capacity** Hyperloop Capsules shall have the following minimum payload capacity.

3.1.1.10.3.1 **Freight** Hyperloop-F configuration capsules provide for carriage of four (4) LD-6, or eight (8) LD-3, or an equivalent combination of LD-6 and LD-3 ULDs. The total gross weight of containers and contents shall not exceed 7,000 pounds for each LD-6 ULD and 3,500 pounds for each LD-3 ULD. Hyperloop-F Capsule payload capacity shall be 28,000 pounds. Payload capacity may be lower under certain operating conditions that differ from the system design point operating conditions. Hyperloop-F configuration Capsules are not fitted to carry passengers or live freight.

3.1.1.10.3.2 **Passengers** Hyperloop-P configuration Capsules provide for carriage of 28 passengers, minimum. Weight per passenger, luggage accommodation, and passenger service provisions are TBD.

3.1.1.10.3.3 **Test Model** Capacity of Hyperloop-T configuration Capsules is TBD.

3.1.1.10.4 **Compression-Lift** Hyperloop Capsules are equipped with a system that takes in gas ahead of the capsule, compresses that gas, routing a portion of the compressed gas to gas bearing “skis” that support the Capsule and expelling any excess compressed gas from the rear of the Capsule. Design, operation and performance of this system, and hence the Capsules is highly dependent on characteristics of the Tube and the ambient conditions within the Tube.

3.1.1.10.4.1 **Compression-Lift Configuration** Capsules employ a compression-lift system which simultaneously compresses gas in front of the Capsule

to allow high speed operation in a relatively small diameter Tube (Kantrowitz limit) and suspends the Capsule above the Tube surface on gas bearings to allow low friction passage of the Capsule along the Tube. The general layout and key elements of the Capsule lift system are shown in Figure 3.1.1.10.4.1-1.

A key aspect of the Compression Lift Configuration is the Intercooler Duct which conveys compressed hot gas from the first compressors to the second compressors at the back of the Capsule while removing compression heat and depositing it into the Tube wall. This Intercooler Duct is open to the Tube wall and sealed against the Tube Wall by the gas bearing skis.

Redundancy in the compressors and gas supply to the gas bearing skis is provided to avoid disablement of a Capsule in transit due to a single point failure of these critical elements.

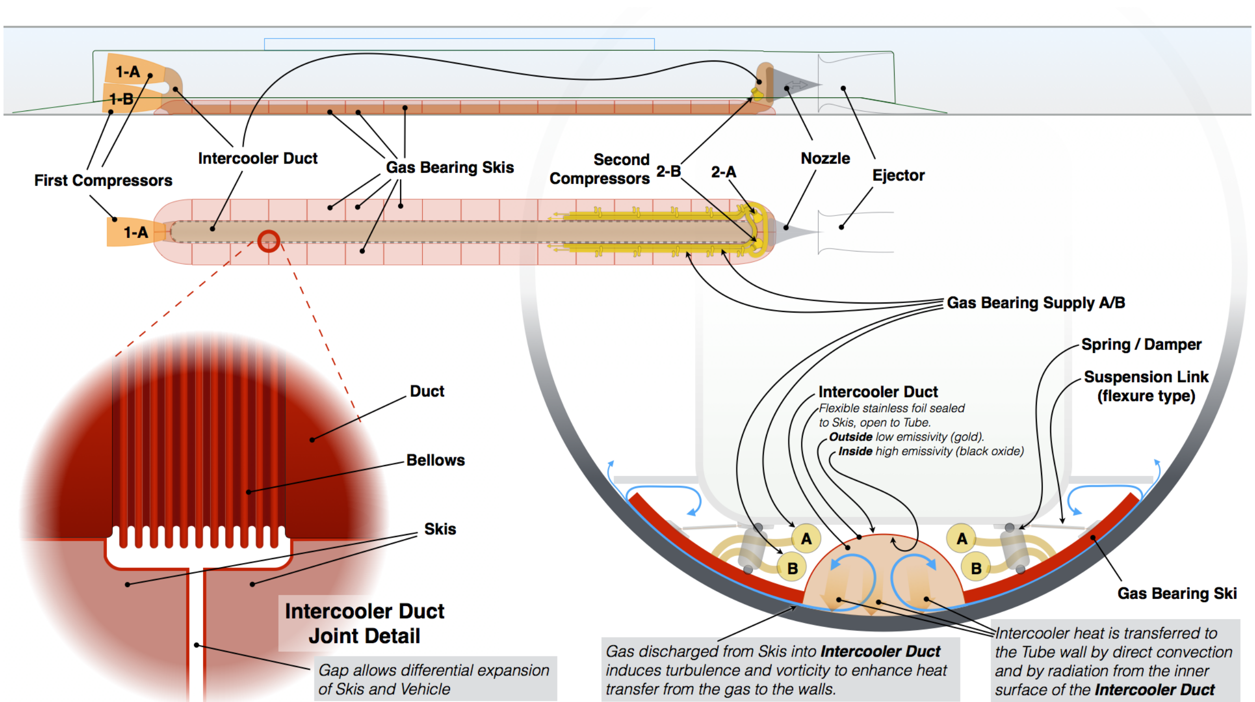


FIGURE 3.1.1.10.4.1-1

3.1.1.10.4.2 **Fill Gas** The Tube will be filled with water vapor at 100 Pa rather than with air. Provisions are required for purging air from the Tube as part of the evacuation process.

Key properties of water vapor and air are listed in Table 3.1.1.10.4.2-1

	Speed of Sound (m/s)	Relative Density	Specific Heat Ratio, k
Air	347	1.00	1.4
Water Vapor	428	0.62	1.327

TABLE 3.1.1.10.4.2-1

3.1.1.10.4.3 **Compression-Lift Cycle** Figure 3.1.1.10.4.3-1 illustrates the design cycle parameters when operating in 100% water vapor at 760 MPH.

note: This compression-lift cycle differs from that of the Hyperloop Alpha document. Instead of having two compression stages and two intercooler stages, this cycle uses only one intercooler. This is possible because the lower 'k' value for water vapor allows a higher pressure ratio in the first compressor while maintaining the same compressor discharge temperature. Further, because the second compressor may now operate at a lower pressure ratio, the intercooler ahead of the second compressor need cool the compressed gas from the first compressor less in order to keep the second compressor exit temperature within reasonable limits.

The intercooler has been configured to also serve as the duct for conveying excess compressed gas from the first compressor to the bypass nozzle. By leaving the bottom of this "Intercooler Duct" open to the tube wall - and using the gas bearing skis to form a moving seal - it becomes possible to dump the required intercooler heat to to Tube wall, which eliminates entirely the need for a water-to-steam thermal sink.

The compression-lift cycle, whether operated with water vapor or with air requires a source of supplemental mass flow at low speeds (typically speeds less than 200 - 250 MPH) to adequately supply the gas bearing skis because at lower speeds the first compressor inlet does not intercept adequate mass flow in the rarified operating environment and becomes 'starved'. The amount of total supplemental mass required varies widely with operating modes because the time the Capsule must travel at low speeds in vacuum while normally short can be several minutes for some off-design conditions. (For example, clearing a queue of capsules stacked up on the vacuum side of the arrival air lock…)

This cycle provides any needed supplemental mass flow from a reservoir of liquid water that is 'evaporated' to 100 Pa, 300 K

conditions, then injected into the first compressor inlet. There are several advantages to this approach:

i) A much smaller, simpler tank is needed to store the supplemental mass.

ii) Introducing supplemental mass into the first compressor requires the entire compression cycle to be working for lift to happen. This means that the compression lift system is 'tested' before the Capsule can leave the airlock - on every trip…

iii) Water vapor introduced into the tube as supplemental mass flow serves to continuously purge the tube of air. Under normal operation the supplemental mass flow will be sufficient to flush the Tube about once a day…

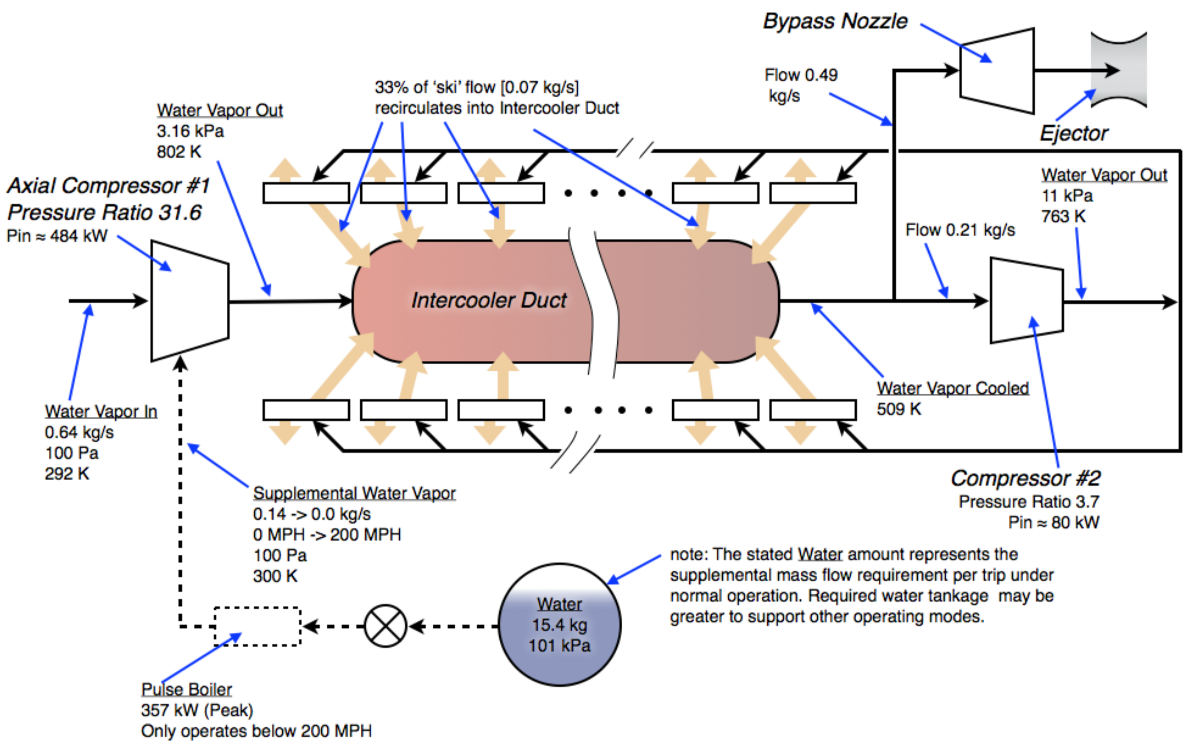


FIGURE 3.1.1.10.4.3-1

3.1.1.10.4.3.1 **Operation With Air - H2O Mixture** The compression-lift system shall operate with Tube fill gas consisting of 0% to 100% water vapor with the balance air. (It will be necessary to do this when the Tube has been initially evacuated, but not yet purged of air.) As the fraction of air in the fill gas increases, the first and second compressors will operate at lower compression ratio (for instance by reducing compressor speed) so as to maintain acceptable compressor discharge temperatures. The result will be that both the overall pressures achieved and the volume flow of air through the compressor system will be lower for higher fractions of air in the Tube fill gas. This will restrict Capsule operating

weight and operating speed. Figure 3.1.1.10.4.3.1-1 and Figure 3.1.1.10.4.3.1-2 show the required Maximum Operating Weight and Maximum Operating Speed as a function of water vapor fraction in the Tube fill gas. *(These curves are "notional" pending detailed cycle analysis and establishment of specific compressor outlet temperature limitations.)*

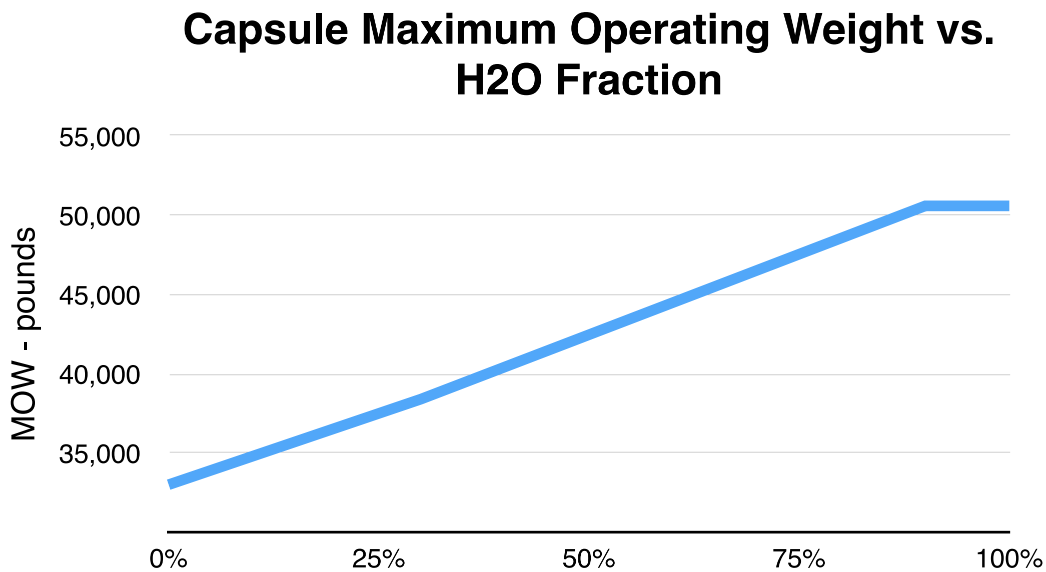


FIGURE 3.1.1.10.4.3.1-1

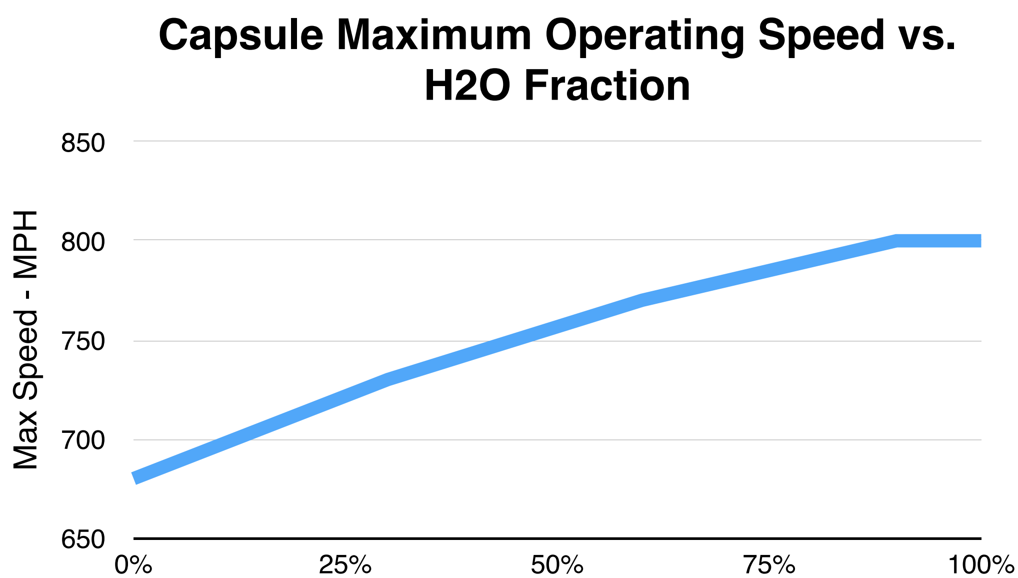


FIGURE 3.1.1.10.4.3.1-2

3.1.1.10.4.3.2 **1 Atmosphere Operation** The Compression - Lift cycle shall operate in air at standard atmospheric pressure and support maximum Capsule Operating Weight (50,600 lbs - TBD) for Capsule speeds between 20 m/s backward and 20 m/s forward, continuously.

3.1.1.10.4.3.3 **Transient Pressure Operatio**n The compression - Lift system shall operate and provide stable lift to the Capsule under the following transient conditions.

3.1.1.10.4.3.3.1 **Airlock Depressurization** Capsule speed zero;101 kPa air down to 100 Pa water vapor; 20 seconds.

3.1.1.10.4.3.3.2 **Airlock Re-pressurization** Capsule speed zero; 100 Pa, 0% - 100% water vapor up to 101 kPa air; 5 seconds

3.1.1.10.4.3.3.3 **Emergency Tube Re-pressurization** Capsule speed up to Maximum Operating Speed (Section 3.1.1.10.4.1); 100 Pa, 0% - 100% water vapor; up to 101 kPa air; time <20 seconds (TBD)

3.1.1.10.5 **Attitude Control** Capsule roll attitude must be precisely controlled to insure that the propulsion rotor will successfully pass through the air gap of the linear motors as they are encountered during passage of the Capsule through Hyperloop. The Capsule roll attitude shall be controlled such that the angular difference between the capsule roll attitude and the combined Capsule acceleration vector (includes acceleration due to gravity) shall be within the range +0.5 degrees and -0.5 degrees. For purpose of this requirement, Capsule roll attitude shall be considered as the vector in the plane perpendicular to the local Tube axial centerline, that connects the propulsion rotor axial centerline with the Tube axial centerline.

3.1.1.10.5.1 **Sensors** Capsule attitude shall be controlled without reference to exterior systems and shall rely on measurements of the capsule composite acceleration vector (vector accelerometers) and Capsule roll rate (rate gyros)

3.1.1.10.5.2 **Dynamic Roll Control**

3.1.1.10.5.3 **Static Roll Trim**

3.1.1.10.6 **Supplemental Propulsion and Mobility** Capsules are equipped with Traction Wheels and Landing Pads which allow Capsules to move at low speed, under their own power while in a Tube or in a Station. Figure 3.1.1.10.6-1 illustrates the arrangement and functionality of the Traction Wheels and Landing Pads.

3.1.1.10.6.1 **Traction Wheels** Each Capsule has four (4) Traction Wheels, two at the front and two at the rear. Each Traction Wheel is driven by a separate in-hub motor that can drive in either direction and also serve as a generator to achieve regenerative braking. Each pair of Traction Wheels at the front and back respectively are mounted to an articulated axel as illustrated in Figure 3.1.1.10.6-1. Traction Wheels can be positioned by the axel to which they are attached in any of three positions designated Retracted, Tube and Station. Traction Wheels on a common axle move together and are maintained in the same position. Axles are maintained perpendicular to the long axis of the Capsule at all times except when Traction Wheels mounted to the axle are in the Station position. When the Traction Wheels are in the

Station position, the axle is free to rotate about a vertical axis aligned with the Capsule center line as shown.

Traction Wheels do not function at any time to support the weight of the Capsule though Traction Wheels are subject to applied force against the Tube wall or against the Station floor as needed to achieve the required tractive force through the Traction Wheel tires.

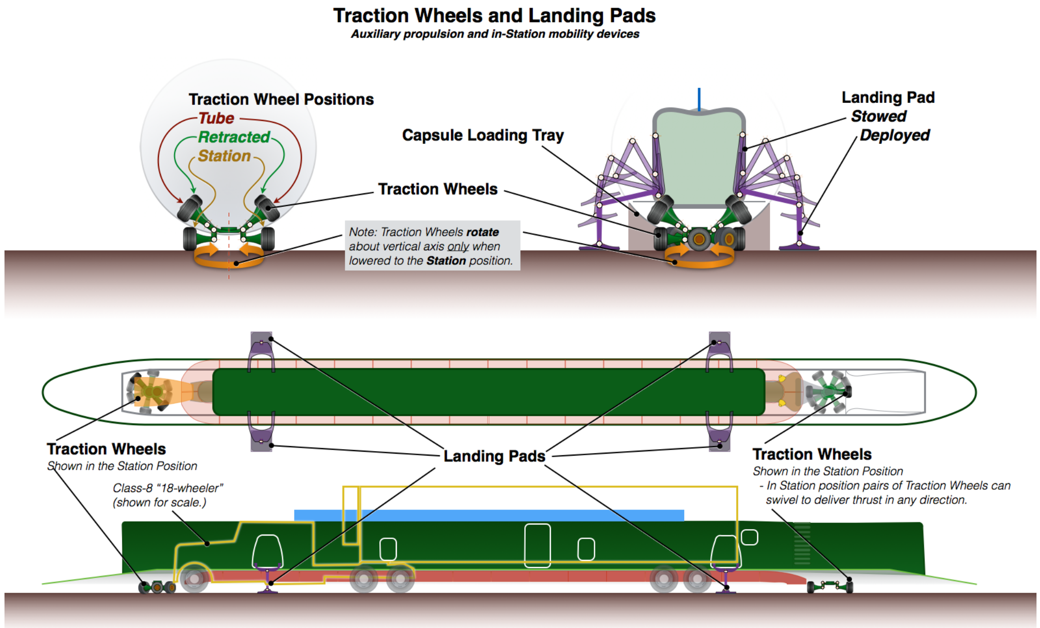


FIGURE 3.1.1.10.6-1

3.1.1.10.6.1.1 **Retracted Position** Traction Wheels are maintained in the Retracted position under normal operating conditions while the Capsule is proceeding at speed. While in the retracted position, Traction Wheels do not contact the Tube wall.

3.1.1.10.6.1.2 **Tube Position** When in the Tube position, Traction Wheels are pressed against the Tube wall. Three functions are performed by the Traction Wheels while in the Tube position.

3.1.1.10.6.1.2.1 **Capsule Positioning in Tube** Traction Wheels provide thrust for positioning the Capsule between the Tube, the Airlock, and the Capsule Loading Tray. Under this operating mode, thrust from the four Traction Wheels in combination shall be sufficient to achieve acceleration / deceleration rates of 2 m/sec2 over the speed range zero to 5 m/sec, forward or reverse.

3.1.1.10.6.1.2.2 **Capsule Propulsion In Tube** Traction Wheels shall propel the capsule at continuous speeds up to 15 m/sec, in the forward or reverse direction while the Capsule is supported by the gas bearings and operating in an nominal 100 Pa or 101 kPa environment. This performance shall be achieved on grades up to and including the steepest design grades on the Hyperloop route. *[This functionality is*

used for a) proceeding to an Access Facility following a Re-pressurization event or b) when clearing Capsules (in vacuum) from the arrival queue or c) when transferring capsules between Access Facilities and Stations while the Tube is a atmospheric pressure.]

3.1.1.10.6.1.2.3 **Emergency Regenerative Braking** Under emergency braking, Traction Wheels shall provide sufficient regenerative braking thrust to achieve a 2 m/sec2 deceleration rate for Capsule speeds between 50 m/sec and zero.

3.1.1.10.6.2 **Landing Pads** Deployable air bearings (Landing Pads) are provided on each Capsule. Landing Pads in combination with the Traction Wheels operating in the Station position allow Capsules to move in any direction (forward, backward, sideways, skew-wise) and to turn while navigating the Station Apron Floor. Landing Pads are supplied with compressed air from a redundant, dedicated, oil-less compressor system that only operates when the Capsule is in a 1 Atmosphere environment. *[The design as illustrated envisions each Landing Pad as being a 2 x 2 array of air bearings similar to Air Castor, Inc. Model AC-22. Diagonal pairs of these air bearings in each Landing Pad are supplied from one or the other redundant Landing Pad compressors on the Capsule. With one of the two compressor systems failed, the "lift" of the Landing Pads is 60,000 pounds, or 119% of the 50,600 pound Capsule design weight.]*

3.1.1.10.7 **Environmental Controls**

3.1.1.10.7.1 **Thermal Control** Capsules provide thermal control to maintain the Capsule payload environment with in the range 23C to 27C. The thermal control system also cools Capsule motors, electronics, batteries and critical assemblies.

3.1.1.10.7.1.1 **Cooling Medium** Cooling of critical Capsule components is achieved by circulated water-glycol. A cold sink, consisting of approximately 1,000 kg of water-alcohol ice slurry is stored in cylindrical tanks, each equipped with a close fitting, rotating agitator. circulating water-glycol is chilled by passing through tubes maintained in thermal contact with the exterior of ice slurry tanks.

3.1.1.10.7.1.2 **Cooling Medium Recharging** Cooling of the ice slurry is achieved by circulating chilled water-glycol from an external chiller through tubes maintained in thermal contact with the ice slurry tanks.

3.1.1.10.7.1.3 **Roll Trim Function** Ice slurry material is contained in pairs of similar size tanks, one tank of a pair on the port side of the Capsule and the other on the starboard side. Each pair of tanks having a combined capacity approximately twice that of the slurry contained are fitted with a slurry pump arranged to transfer slurry between the tanks. This arrangement allows shifting the approximately 1,000 kg mass of ice slurry between tanks and provides Capsules with the means to adjust static roll trim.

3.1.1.10.7.2 **Humidity Control**

3.1.1.10.7.3 **Carbon Dioxide Control**

3.1.1.10.7.4 **Oxygen Control**

3.1.1.10.7.5 **Pressure Control**

3.1.1.10.8 **Energy Storage**

3.1.1.10.9 **Accommodations**

3.1.1.10.9.1 **Freight Accommodations** Hyperloop-F configuration capsules accommodate freight carried in modular containers - Unit Load Devices (ULD) that are also used by the commercial airline industry.

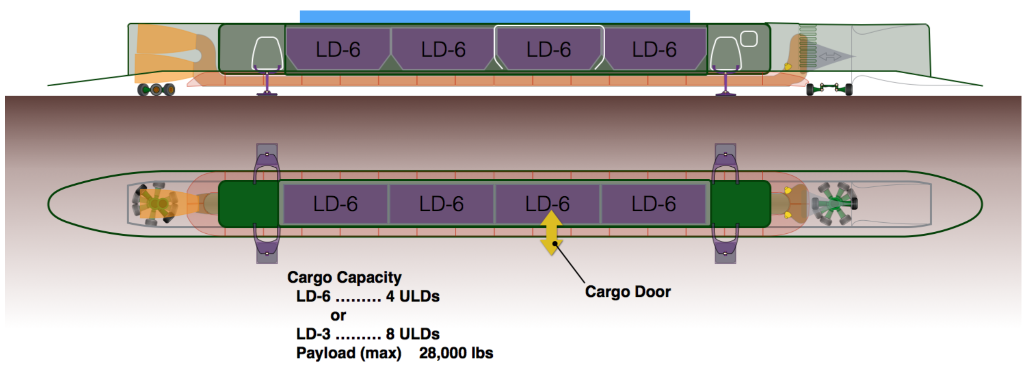


FIGURE 3.1.1.10.9.1-1

3.1.1.10.9.2 **Passenger Accommodations** Hyperloop-P Capsules accommodate up to 28 passengers. Cabin layout and dimensions are Illustrated in Figure 3.1.1.10.9.2-1

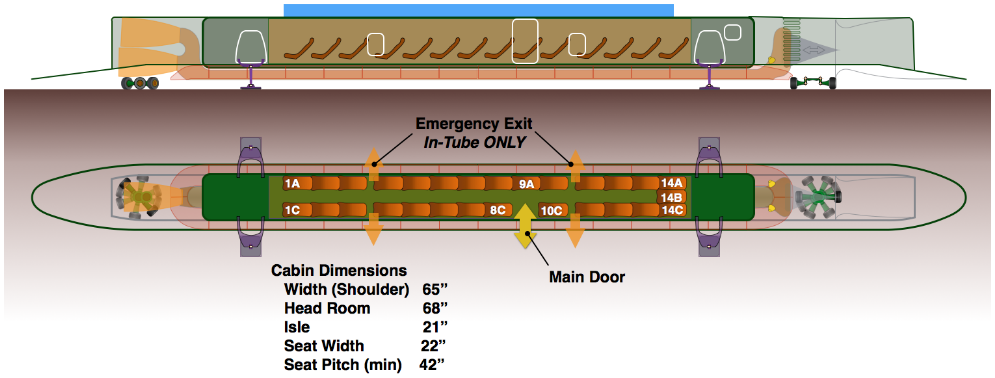


FIGURE 3.1.1.10.9.2-1

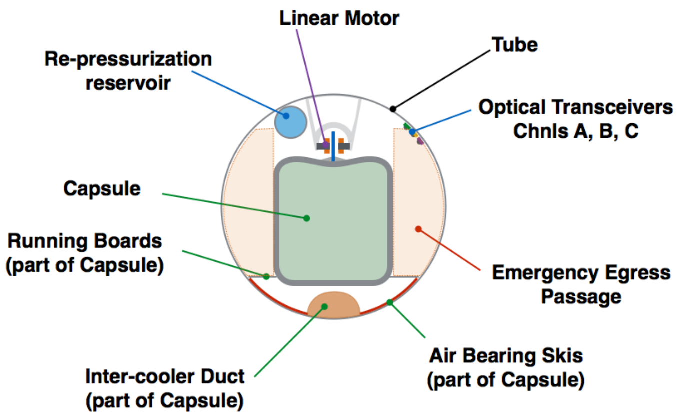
3.1.1.10.9.3 **Testing Accommodations** (TBD)

3.1.1.10.xxx **Mission Profile**

3.1.2 **Interfaces**

3.1.3 **Major Components**

3.1.3.1 **Tube** Figure 3.1.3.1-1 illustrates the Tube Cross Section and the relation of Tube Elements within the Tube and in reference to a Capsule located in the tube.



Tube Cross Section Diagram
(Capsule shown for reference only.)

FIGURE 3.1.3.1-1

3.1.3.1.1 **Internal Diameter** The Tube internal diameter shall be 3.43 m (135 in).

3.1.3.1.2 **Tube Elements - Internal** The following elements of the Tube are located inside the Tube and generally disposed as illustrated in Figure 3.1.3.1-1.

3.1.3.1.2.1 **Re-pressurization Reservoir** The Re-pressurization Reservoir and associated plumbing, valves, control and measurement equipment shall be located inside the Tube in the area indicated and shall not interfere with the Capsule (particularly the linear motor “rotor”) for capsule bank angles within the range of -45 deg. to +45 deg. or intrude on the illustrated Emergency Egress Passage area.

3.1.3.1.2.2 **Linear Motors** Linear motors that provide for Capsule propulsion and deceleration shall be aligned with the Tube vertical centerline. Linear motor shall only be located in straight Tube sections (radius of horizontal or vertical curvature > TBD)

3.1.3.1.2.3 **Optical Transceivers** Optical transceiver units for communication channels A, B and C are located on the inside surface of the Tube as indicated. An uninterrupted line of sight shall exist between Optical Transceivers on the inside of the Tube and corresponding Transceivers located on the Capsule (at the front and rear of the Capsule, top of capsule body on centerline) for any Tube mounted Transceiver located between zero and 50 m ahead of the front of a Capsule or between zero and 50 m behind the rear of a Capsule as the capsule passes through the tube. This non-blocking alignment requirement shall be met a) everywhere along the Tube, b) for Capsule bank angels from 0

degrees to the maximum design path bank angle and c) for each channel independently.

3.1.3.1.2.3.1 **Longitudinal Spacing** Optical Transceivers for each one channel, (A, B or C) shall be spaced longitudinally every 40 ± 5 m. Transceivers for channels A, B and C need not be co-located longitudinally.

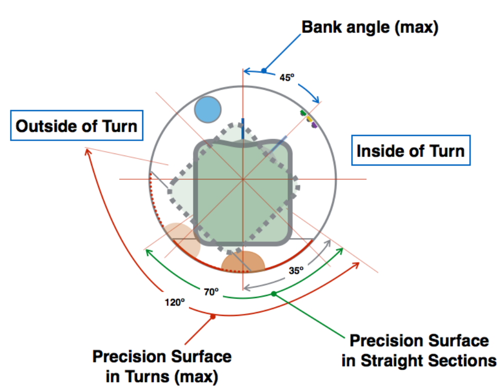
3.1.3.1.3 **Tube Interior Surface** The interior surface of the Tube shall have the following properties.

3.1.3.1.3.1 **Surface Emissivity** Emissivity of the inner tube surface shall be not less than 0.2 at any wavelength from 1μm to 10 μm and the average interior surface emissivity weighted by the 700K blackbody radiation characteristic over the wavelength range 1 μm to 10 μm shall be > 0.6. These minimum emissivity levels shall be maintained over the operating life of the Hyperloop.

3.1.3.1.3.2 **Surface Accuracy** The maximum surface deviation from the least squares fitted design surface profile shall not exceed the values listed in Table 3.1.3.3.2-1 over the portion of the Tube indicated as "Precision Surface" in Figure 3.1.3.1.3.2-2.

Length Scale (meters)	Maximum Absolute Deviation (mm)
10	0.5 (TBD)
100	1.5 (TBD)
1,000	5.0 (TBD)
10,000	25 (TBD)

TABLE 3.1.3.1.3.2-1



Tube Interior Precision Surface Region
(Capsule shown for reference only.)

FIGURE 3.1.3.1.3.2-2

3.1.3.2 **Capsules**

3.1.2.2.1 **Dimensions**

3.1.2.2.2 **Compressor and Suspension**

3.1.2.2.3 **Battery Power System**

3.1.2.2.4 **Environmental Control System**

3.1.2.2.5 **Servicing Interface**

3.1.2.2.6 **Auxiliary Propulsion**

3.1.3.3 **Stations**

3.1.3.4 **Communication and Control System**

3.1.4 **Externally Supplied Items** Several components of Hyperloop are supplied from external sources as standard commercial items or services, or are obtained by way of or a a derivative of existing commercial, public, municipal or Government services.

3.1.4.1 **Grid Power**

3.1.4.2 **Rights of Way**

3.1.4.3 **Emergency Services**

3.1.4.4 **Security and Law Enforcement Services**

3.1.4.5 **Safety Verification and Oversight**

3.2 **Characteristics**

3.2.1 **Performance Characteristics**

3.2.1.1 **Operating Modes** Hyperloop operates in the following modes.

3.2.1.1.1 **Two Tube Operating Flow**

3.2.1.1.2 **Single Tube Operating Flow**

3.2.1.1.3 **Maintenance and Rescue (Tube at 1 Atm.)**

3.2.1.1.4 **Speeds**

3.2.1.1.5 **Cycle Timing**

3.2.1.2 **Environmental Control**

3.2.1.3 **Emergency Operation**

3.2.1.3.1 **Emergency Stop**

3.2.1.3.2 **Emergency Re-pressurization**

3.2.1.3.3 **Extraction**

3.2.1.4 **Tube De-pressurization and Purging**

3.2.1.5 **Design Point Missions** Design of Hyperloop and its components shall provide for the following mission scenarios.

3.2.1.5.1 **Normal Passenger Mission** Figure 3.2.1.5.1-1 illustrates the timing and performance required of Hyperloop-P configuration with design point Tube fill gas (100 Pa, >95% water vapor). *(Consumable utilization is estimated, pending analysis)*

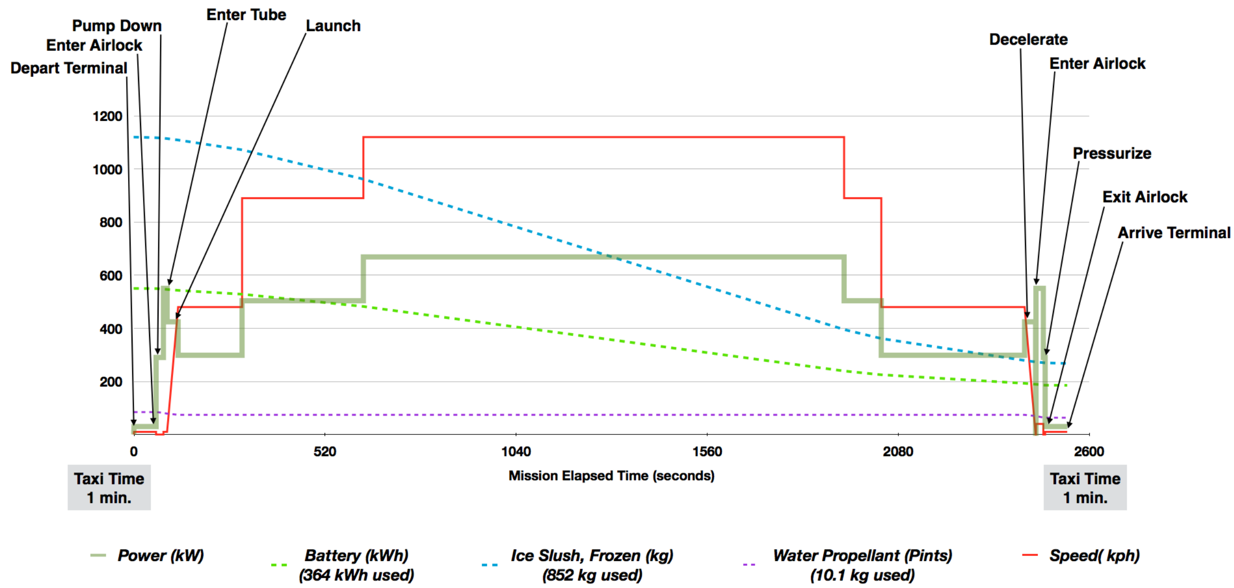


FIGURE 3.2.1.5.1-1

3.2.1.5.2 **Self-Powered Tube Transit** Hyperloop Capsules shall be capable of traveling between Stations under internal power when the Tube is at normal atmospheric pressure. Capsules shall also be capable of transit from any Access Facility to either Station under internal power when the Tube is at normal atmospheric pressure. Figure 3.2.1.5.2-1 illustrates the time line for a Station to Station transit of a Capsule operating under 1 atm conditions. *(This capability is intended to allow repositioning of Capsules to a Station after Capsules have been extracted from the Tube at Access Facilities - typically following an emergency stop / re-pressurization event. This capability also allows for sending a Capsule through the Tube to inspect the interior, test the communication channels (section 3.1.1.3), and verify the absence of people or foreign objects within the Tube prior to beginning the evacuation process.*

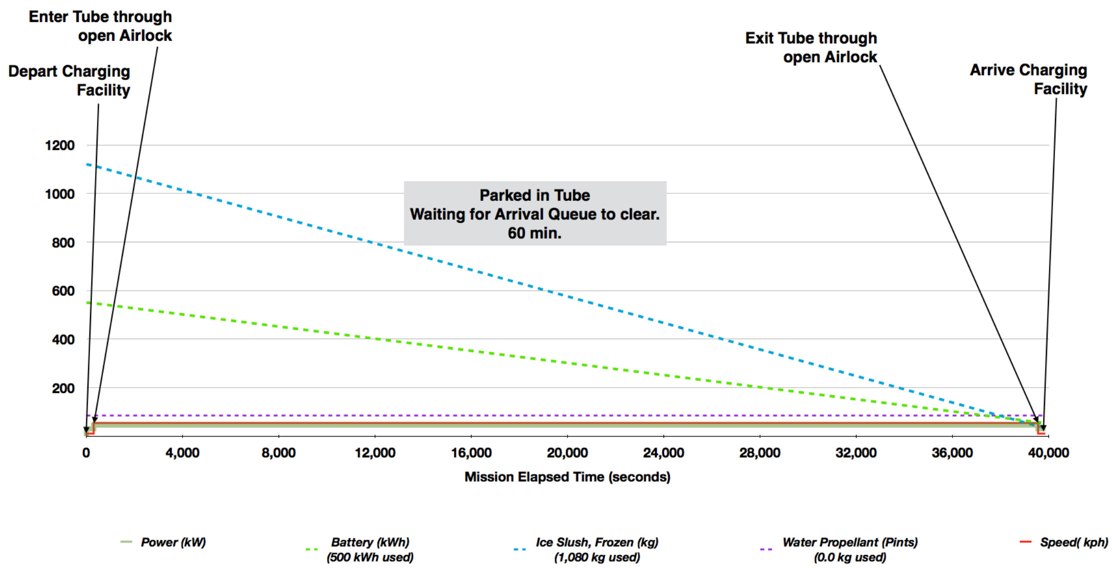
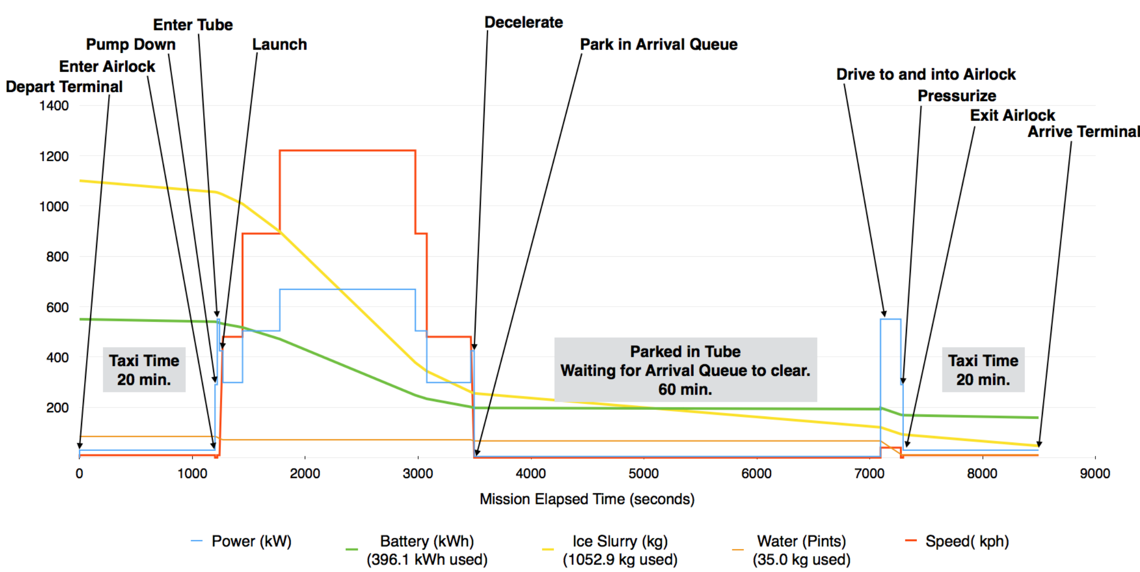


FIGURE 3.2.1.5.2-1

3.2.1.5.3 **Congestion Delay** Hyperloop shall accommodate finite delays due to congestion or other uncontrollable and randomly occurring events without the necessity of re-pressurization of the Tube. A representative congestion delayed mission timeline is illustrated in Figure 3.2.1.5.3-1



FIRGUE 3.2.1.5.3-1

3.2.1.6 Energy Generation, Utilization and Storage

3.2.1.7 Communications

3.2.1.8 **Environmental**

3.2.1.8.1 **Noise Levels**

3.2.1.8.2

3.2.2 **Physical Characteristics**

3.2.3 **Reliability**

3.2.4 **Maintainability**

3.2.5 **Environments**

3.3 **Design and Construction**

3.3.1 **Parts, Materials and Processes**

3.3.2 **Electromagnetic Compatibility & Data Security**

3.3.3 **Workmanship**

3.3.4 **Interchangeability**

3.4 Major Component Characteristic

4. Quality Assurance

4.1 General

4.1.1 Responsibility

4.1.2 Special Tests and Examinations

4.2 Verification

5. Preparation for Delivery

6. Notes